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Environmental life cycle assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels and conventional trawls—LCA methodology with case study

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Abstract
Background, aim, and scope Two fishing methods, creeling and conventional trawling, are used to target Norway lobster (*Nephrops norvegicus*), economically the second most important species in Swedish west coast fisheries. The goal was to evaluate overall resource use and environmental impact caused by production of this seafood with the two different fishing methods using life cycle assessment (LCA) methodology.
Materials and methods The inventory covered the entire chain starting by production of supply materials and the fishery itself, through seafood auctioning, wholesaling, retailing, to the consumer. That portion of the life cycle occurring on land was assumed to be identical for Norway lobsters regardless as to how they were caught. The functional unit was 300 g of edible meat (i.e., Norway lobster tails), corresponding to 1 kg of whole, boiled Norway lobsters. The seafloor impact of trawling was quantified using a recently developed methodology.
Results Major differences were found between the fishing methods with regard to environmental impact: creeling was found to be more efficient than conventional trawling in all traditional impact categories and in the two additional fishery-related categories involving seafloor impact and discarding. Since the quality of the creel-caught *Nephrops* was higher, the difference was probably even higher than indicated here.
Discussion Major improvement potential was identified in the more widespread use of creels and species-selective trawls. The only deficiencies of creel fishing were poorer working environment and safety, and a potentially higher risk of recruitment overfishing. However, these issues could be handled by technological development and fisheries regulations and should not hamper the development of creel fishery.
Conclusions Improvement options were identified and quantified for the Swedish *Nephrops* fishery. The study demonstrates how LCA can be used to compare the environmental performance of different segments of a fishery.
Recommendations and perspectives Shifting to creeling and species-selective trawling would lead to considerably lower discard, fuel use, and seafloor impact while providing consumers with the same amount of Norway lobsters.

Keywords Creels · Discard · Fuel use · LCA case study · *Nephrops* · Norway lobster · Seafood · Seafloor impact · Trawls

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1 Background, aim, and scope

Annual global landings of Norway lobster, a species occurring along the eastern shelf of the Atlantic from Iceland and northern Norway down to Morocco, and extending into the Mediterranean Sea, are just below 60,000 tonnes (FAO 2007). Main fishing nations are the United Kingdom (50%) and Ireland (14%).The Swedish *Nephrops* fishery lands less than 2% of the global landings

and takes place along the western coastline of the country in the easternmost parts of the North Sea, the Skagerrak and Kattegat. Annual Swedish *Nephrops* landings have fluctuated around 1,000 tonnes since the mid 1980s. Approximately 100 trawlers, accounting for 80% of total *Nephrops* landings are active in this fishery. The Swedish creel fishery for *Nephrops* started in the mid 1980s and produced approximately 10% of the total landings until the late 1990s. Between 1999 and 2005, the number of creel fishing vessels increased by 50% to 110 and, in 2005, creeling produced approximately 20% of the total landings, mainly from the northern part of the area, the Skagerrak (Swedish Board of Fisheries, personal communication). A typical *Nephrops* creel is depicted in Fig. 1a. These are baited with

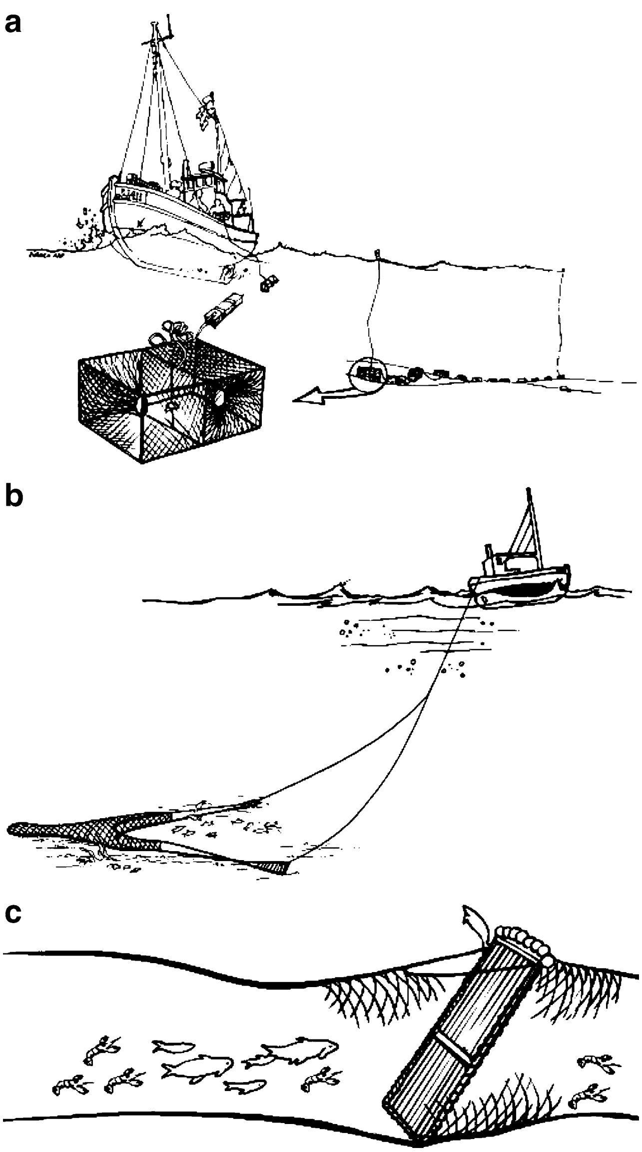

Fig. 1 Fishing gear used along the Swedish west coast to target Norway lobster **a** creel, **b** conventional single trawl, and **c** species-selective grid trawl (illustrations by Jürgen Asp)

salted herring to attract the target species and are typically fished in fleets consisting of 30–60 creels. The herring is either bought from large dedicated herring seiners or fished with pelagic trawls in the winter. Trawls in this fishery use a minimum mesh size of 90 mm and are either single otter trawls like that depicted in Fig. 1b or twin trawls, i.e., two trawls pulled in parallel. Norway lobsters are found on the seafloor or in approximately 10-cm-deep burrows under the seafloor surface, hence the trawl has to be dragged along the seafloor. Due to the high amount of by-catch and discard of groundfish in the conventional *Nephrops* trawling, the use of a species-selective grid (i.e., trawls equipped with a Nordmore-type sorting grid with a 35-mm bar distance and a 70-mm square mesh codend, depicted in Fig. 1c) is mandatory in Swedish national waters since 2004. The grid in the upper part of the trawl lets the fish escape through it, while the target species is retained on the bottom of the trawl. This legislation was introduced with the aim of significantly reducing the fishing mortality of the juveniles and adults of local populations of demersal fish species such as cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), stocks that are currently on historically low levels, and to protect habitats sensitive to trawling disturbance (Anon 2006). In 2005, 34% of Norway lobster catches were landed by trawls with sorting grids, 46% by conventional trawls, and 20% by creels. The compositions of the catches obtained using the three fishing methods are presented in Fig. 2. While the differences between the fishing methods with regard to catches and landings are becoming known (Valentinsson and Ulmestrand 2008), a holistic assessment (i.e., including seafloor impact and energy use, for example) of the overall environmental impact of fishing *Nephrops* with trawls and creels is lacking.

2 Materials and methods

2.1 Goal and scope

This study aimed at quantifying the resource use and environmental impact associated with the production and consumption of Norway lobsters caught by creels and conventional trawls. The species-selective trawl was not included due to lack of similar data as obtained for the other two fishing methods. Norway lobster was chosen as the subject species because it is the economically most important fishery in the Kattegat and due to the availability of marine habitat maps for this area. A method to quantify the seafloor impact of active fishing gear was developed in a previous study (Nilsson and Ziegler 2007). The use of the method in the Norway lobster case study represents its first application in a seafood life cycle assessment (LCA), see section 2.3. The functional unit was 300 g of Norway

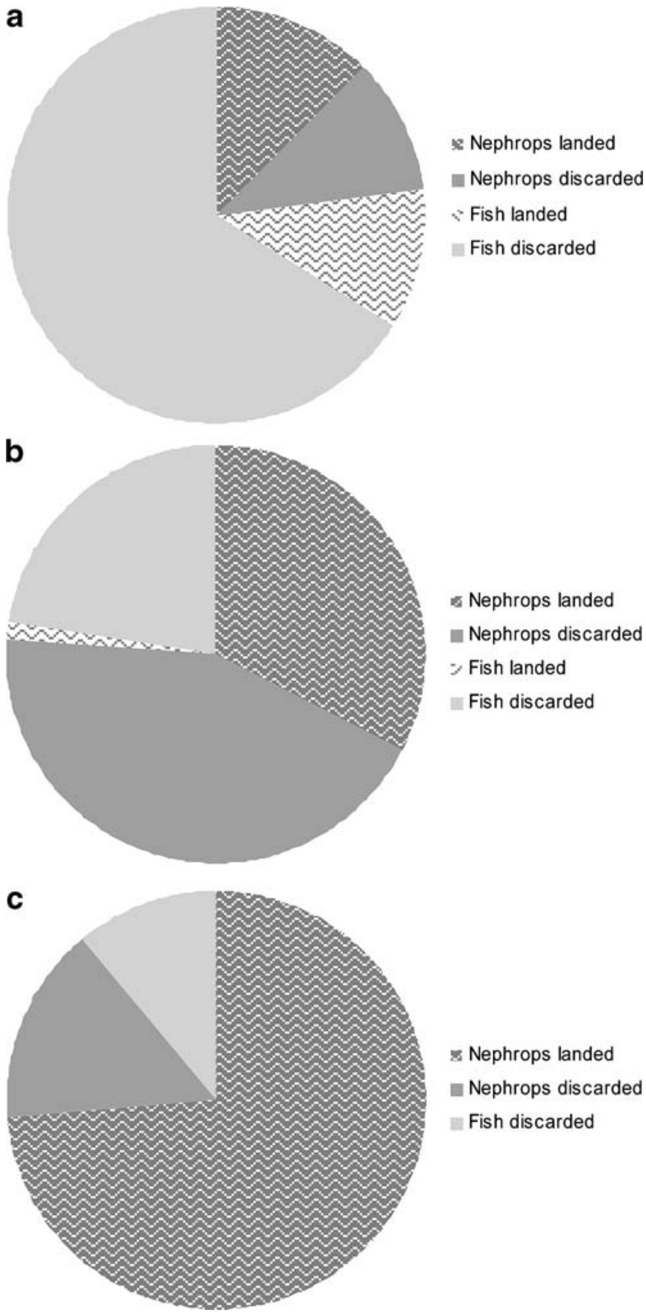

Fig. 2 Composition of the catches obtained using the three fishing methods (mass): **a**–**c** conventional *Nephrops* trawl (90-mm diamond mesh codend). Note that no estimates of natural and discard mortality are included here as is done later. Average values for 2004–2005

lobster tails (three servings) of average-sized Norway lobsters bought boiled from a seafood retailer in Göteborg to be consumed cold in private households. With a product yield of 30%, the functional unit corresponds to 1 kg of landed Norway lobsters. Two different fishing methods were included: creeling and conventional trawling. The life cycle on land was assumed to be identical for Norway lobsters regardless as to how they were caught. The product was followed starting from the production of supply materials, such as fuel, electricity, and packaging materials, through the fishery, transport, retail, and consumer phases. The life cycle ends with municipal sewage treatment, which releases the nutrients contained in the Norway lobsters back to the sea.

2.2 Data sources

A questionnaire asking about approximate fuel consumption, catches, gear types, gear material, anti-fouling, and other chemical agents, and product quality was sent to the 78 fishermen who according to official fishery statistics, had reported landings of more than 1,000 kg of Norway lobster in two consecutive years, 2002 and 2003. We chose to target fishermen with Norway lobster fishing as their main occupation. Answers from 19 of these fishermen were used, 12 of whom used creels and seven conventional trawls. The Swedish Board of Fisheries provided data from their statistical database which is based on logbook data concerning all landings of *Nephrops* in the Kattegat and Skagerrak in 2005. Data concerning the composition of the catch using the species-selective trawl were gathered via on-board observer programs in 2004 and 2005, as reported in Valentinsson (2006). Additional data were collected from companies involved in the production chain of Norway lobsters and LCA databases, primarily Ecoinvent v.1.2 (Anon 2000) and were used to obtain data concerning, for example, diesel, electricity, and packaging paper production. Data for the herring fishery to produce the bait was taken from Thrane (2004a). Emissions produced by diesel combustion were modeled as by Ziegler and Hansson (2003), for more details, see Electronic Supplementary Material.

2.3 Seafloor impact assessment

The questionnaire mentioned above also asked about approximate gear dimensions, that is the width of the trawl opening and length of the trawl boards and the width and length of the creels. From this data, we calculated an index of area swept per hour trawled. For the creel fishery, the average area of a creel was determined from the questionnaire, as was the average number of creels used per single occasion. These figures and the total number of efforts that had occurred in the area (Skagerrak and Kattegat) in a year were multiplied, and the result was then divided by the total Norway lobster catch to obtain the average seafloor area used per unit of landed catch in the creel fishery. The fishing effort data (hours trawled) for different gear types provided by the National Board of Fisheries were multiplied by the gear index of each trawl type considered to be used to target Norway lobster, and then divided by the total catch reported in the same data in order to obtain a rough

estimate of the average seafloor area swept per unit of landed catch in the trawl fishery. Nilsson and Ziegler (2007) developed a methodology for spatially analyzing demersal fishing effort data, which was applied in the present case study. Geographic information system (GIS) analysis was hence performed in order to assess the intensity and biological impact of the seafloor impact on the benthic habitats occurring in the area. Fishing positions (gear set position) in longitude and latitude were transformed to decimal degrees and the data were then imported into the ArcMap 9.0 (ESRI 2004) GIS software package. A map of marine habitats, classified according to the European Nature Information System (Anon 2002), also used in Nilsson and Ziegler (2007), was also imported. The fishing effort dataset was then overlaid with the habitat map and fishing intensity was analyzed in 5×5 km squares by applying the neighborhood statistics function in the ArcMap extension Spatial Analyst, both for the entire area and for each marine habitat type separately. The analysis produced estimates of the total proportions of each habitat and of the entire area affected by fishing and fishing intensity (for each habitat and for the entire area). The biological impact of the fishing intensities found was evaluated using a British database (MarLIN) containing information on the sensitivity and recoverability of marine species and habitats from fishing disturbance (Anon 2004), as was done by Nilsson and Ziegler (2007).

2.4 Discard

Discard data from conventional *Nephrops* trawls were provided by onboard observer programs examining the catches of commercial fishing vessels, and were expressed in terms of kilogram of undersized *Nephrops* and fish discarded per kilogram landed for the gear types and hauls targeting *Nephrops* (Y. Walther, personal communication). The main types of discard are described regarding species and amounts. Discard data for the species-selective trawl were gathered from the first evaluation of the regulation introduced in 2004 (Valentinsson 2006). These data were gathered as part of the same onboard observer program, examining the catches of commercial vessels using both conventional and species-selective trawls in 2004 and 2005. Discard mortality estimates for *Nephrops* were found in Ulmestrand et al. (1998).

2.5 Co-product allocation strategies

In the fishery, allocation to the different by-catch species was done on the basis of their economic value (annual average values were used). System expansion, the method to handle co-products recommended by ISO (2002), was not considered to be feasible as there are no fisheries landing each one of the by-catch species separately. Allocating based on the energy content, in this case, would be similar to a mass allocation and the logic behind choosing economic allocation was that it is the high economic value of the Norway lobsters that drives this fishery, not the lower value by-catch that is also landed. In storage and transports, volume or mass allocation is sometimes considered to be the most appropriate choice (Ziegler et al. 2003; Thrane 2004a; Ayer et al. 2007). In this case, however, storage was not limited by mass or volume, neither at the auction, wholesaler, nor retailer, which is why economic allocation was chosen in these phases too. Rather, storage capacity was much greater than what was actually used. For transports, all the impact was attributed to the crayfish (no transportation of other goods was assumed) as a 'worst case' both due to lack of information on the detailed logistics around Norway lobster transportation and due to an interest in seeing this "worst" case would contribute significantly to the overall environmental impact.

2.6 Software and impact assessment methods used

The present LCA was performed using the software SimaPro Analyst 6.0.4 (PRé Consultants 2004) and the characterization method chosen was the one developed at the Institute of Environmental Sciences (CML) at Leiden University, the Netherlands, CML baseline 2000 (v. 2.03). Of the impact categories included in the CML method, freshwater, terrestrial, and human toxicity were excluded due to uncertainties in the results identified by Ziegler (2006), and ozone depletion potential was excluded because of data gaps described in the same report, i.e the categories included were abiotic depletion, global warming potential, marine toxicity, photochemical oxidation potential, eutrophication potential, and acidification potential. For more details concerning the methodology used in this case study, see Electronic Supplementary Material.

3 Results

3.1 Discard

The amount of discard of all species killed in the conventional trawl fishery was calculated to be 4.5 kg per kilogram of *Nephrops* landed, of which 0.4 kg were undersized *Nephrops* and 4.1 kg were undersized fish. The natural mortality of Norway lobsters (25%) and fish (20%) was accounted for as were the different discard mortality rates of the different species (i.e., discard mortality of Norway lobster 75%, of fish 100%). The main species discarded during conventional trawling were cod (*G. morhua*), flounder (*Platichthys flesus*), *Nephrops*, dab (*Limanda limanda*), whiting (*Merlangius*

merlangus), plaice (*Pleuronectes platessa*), long rough dab (*Hippoglossoides platessoides*), edible crab (*Cancer pagurus*), gurnard (*Eutriglia gurnardus*), and hake (*Merluccius merluccius*).

Species-selective trawling led to considerably lower discards and landed by-catch, a total of 1.35 kg per kilogram of *Nephrops* landed, of which 0.82 kg were undersized *Nephrops* and 0.53 kg were undersized fish. The discard of undersized fish was hence 87% lower and total discards (i.e., including *Nephrops* discards) were 70% lower than in conventional trawling. The higher discard of *Nephrops* is due to the fact that the selective fishery occurs mainly in national waters located closer to shore that are hence fished more intensely. The landed by-catch decreased from 73% to 6.6% of total catch by weight (Valentinsson 2006). The main species discarded during selective trawling were *Nephrops*, dab (*L. limanda*), long rough dab (*H. platessoides*), plaice (*P. platessa*), cod (*G. morhua*), whiting (*M. merlangus*), witch (*Glyptocephalus cynoglossus*), hake (*M. merluccius*), flounder (*P. flesus*), and gurnard (*E. gurnardus*).

Discards in the creel fishery were even lower, 0.36 kg per kilogram of Norway lobster landed (Anon 2006); of this, 0.21 kg were undersized *Nephrops* and 0.15 kg were undersized fish. A large part of the fish can be assumed to die, while 99% of the discarded creel-caught lobsters survive (Wileman et al. 1999), hence approximately 0.15 kg (assuming 100% mortality for lack of other figures) of fish discard is killed per kilogram of creel-caught *Nephrops* landed. In the creel fishery, the main species discarded were *Nephrops*, cod, sea scorpion (*Myoxocephalus scorpius*), swimming crab (*Liocarcinus depurator*), spider crab (*Hyas* sp.), edible crab (*C. pagurus*), poor cod (*Trisopterus minutus*), whelk (*Neptunea antiqua*), hermit crab (*Pagurus bernhardus*), and squat lobster (*Munida rugosa*).

3.2 Seafloor impact assessment

The seafloor area swept by conventional *Nephrops* trawls was calculated to be approximately 15,000 m^2 per kilogram of catch. After economic allocation (59% of the economic value of the catch was represented by *Nephrops*) and consideration that only 27% of the catch (by weight) was Norway lobster, the result was that 33,000 m^2 were swept per kilogram of *Nephrops* landed (corresponding to a square 182×182 m in size).

Results of the GIS analysis indicated that 29% of the total Kattegat area was affected by the trawl fishery in 2003. In muddy seafloor areas that are the natural habitat of Norway lobsters, 86% of the area was affected by the fishery. Other habitats affected were sandy habitats (58% affected), combination sediments (59% affected) and deep rocky habitats (100% affected). The last result is partly due to the small total size and patchy distribution of this habitat in relation to the size of the analyzed squares (which was inescapable due to the resolution of the trawl effort data); there could have been overestimation, so the result should not be over-interpreted. Nevertheless, the borders between muddy and rocky areas are known to be good fishing grounds for both Norway lobsters and for some important fish by-catch species. Intensity was likewise highest in muddy areas. Muddy areas were on average swept 2.5±2.9 (average±standard deviation) times per year; a considerable proportion of the muddy habitats (36%) was swept more than twice per year and 15% was swept more than four times per year. Disturbance intensity was lower in the other habitats, including the deep rocky ones. Almost the entire remaining area was affected less often than twice per year by these trawlers.

The recoverability of muddy habitats from fishing disturbance, according to the MarLIN database (Anon 2004), is high, indicating complete recovery in 6 months to 5 years after a single fishing event. This would indicate than any muddy area being affected more often than twice per year remains in a continuously disturbed condition, which in this case corresponding to 36% of the habitat (or 1,242 km^2). Hence, 1,242 km^2 are kept in a permanently altered condition due to *Nephrops* trawling that lands approximately 246 tons of Norway lobster from the area, indicating that approximately 3,000 m^2 per kilogram of Norway lobster landed (corresponding to a square 55×55 m in size) are permanently disturbed, given the current level and distribution of the conventional trawl fishing effort.

The area impacted by the creels was much smaller. The entire west coast creel fishery, landing 20% of the total lobster catch affected the same seafloor area as did 1 hour of trawling. The seafloor affected by creels per kilogram of catch (99% of the economic value of the catch comes from Norway lobsters) was calculated to be 1.8 m^2. Due to the enormous difference in seafloor impact between the trawl and creel fisheries, no effort was made to analyze intensity as was done for the trawl fishery. The analysis did not take into account the potential sea floor disturbance caused by dragging of the rope connecting the creels in each fleet.

3.3 Energy use

Figure 3 shows that the fishery itself is the phase in which most energy is consumed. Energy use after landing represents just 10% of the total life cycle energy use for conventionally trawled and 32% for creel-fished Norway lobsters. Energy use in the fishing phase is extraordinary. To catch 1 kg of Norway lobsters using conventional trawling, 325 MJ are used in the form of diesel. For the creel fishery this figure is 80 MJ (of which approximately 10% comes from the bait herring fishery). In the creel

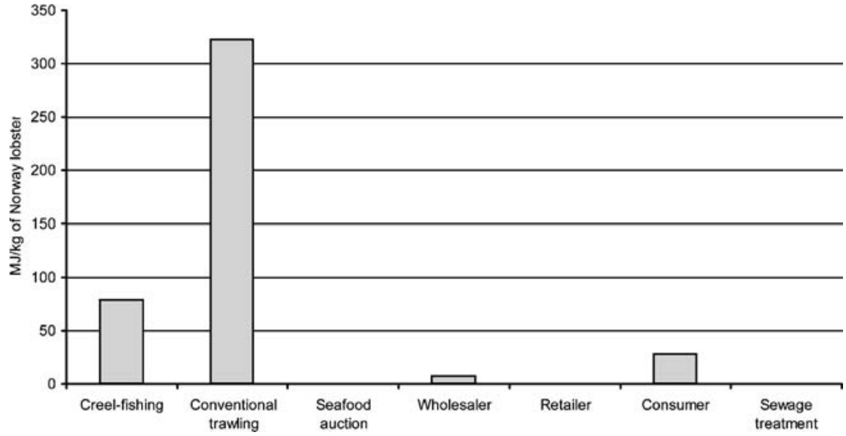

Fig. 3 Energy use in the life cycle of a kilogram of Norway lobster. Creel fishing and conventional trawling represent alternative fishing methods

fishery Norway lobster represents 97% by weight and 99% by value of the landings, and 2.2 l of diesel were used per kilogram of *Nephrops* landed. In the conventional trawl fishery, Norway lobster represents 27% by weight and 59% by value of the catch, and 9.0 l of diesel were used per kilogram of *Nephrops* landed. Obviously, there is a pronounced difference in energy use between the fishing methods.

3.4 Impact assessment results

The process of fishing is dominant in terms of environmental impact in both cases, more markedly so for conventionally trawled *Nephrops* than for those caught by creels. Diesel combustion and diesel production determine this result. Other important phases are the transport home from the retailer, and bait and gear production for the creel fishery. In one impact category, photochemical oxidation, the impact of transport home even exceeds the creel fishery itself. The results of the impact assessment are presented in Fig. 4 and in Tables 1 and 2.

3.5 Sensitivity analysis

We conducted a sensitivity analysis of the five aspects considered to have the greatest impact on the overall results: fuel use, two allocation decisions, product yield, impact assessment method, and background data chosen. One variable was changed at a time and the impact on overall results follows. The ranges (standard deviation) of the fuel use of the two fishing methods overlapped slightly, the range of conventional trawling was 14–50 kg CO_2 eqs. (mean, 32 kg CO_2 eqs.), and the range of creel fishing was 7.0–15 kg CO_2 eqs. (mean, 11 kg CO_2 eqs.). When the fuel consumption in conventional trawling was one SD lower and in the creel fishery one SD higher than the mean, the two fisheries produced similar amounts of global warming emissions. However, this was considered an unlikely scenario due to the significant difference between the two data sets seen originally. In conclusion, variation of this important aspect was considerable, but the difference between averages of the fishing methods was large and statistically significant, which is why we believe that the conclusion is robust. More detailed data concerning the fuel consumption in these fisheries would be most useful.

Allocating based on the same prices as used previously, but with the catch composition as reported in the questionnaires, in which the creel fishery was found to use 2.2±1.2 l diesel (average±standard deviation) per kilogram of Norway lobster landed (*Nephrops* representing 86% of the catch value as opposed to 99% as reported in the logbook-based fishery statistics). Conventional trawling used 8.6±4.2 l diesel per kilogram of Norway lobster landed (*Nephrops* representing 70% of the catch value as opposed to 59% as reported in the statistics). The ranges do not overlap and the difference between the two is statistically significant (Fig. 5). If allocation were based on the landings as recorded in the logbooks, the difference between the fishing methods would increase further, global warming emissions increased from 32 to 37 kg CO_2 eqs. for conventional trawling and decreased from 11 to 10 kg CO_2 eqs. for creel fishing.

Allocating smaller parts (10% and 50% instead of 100%) of the total environmental impact caused by transport home to the Norway lobsters caused no major changes in the results, but decreased the importance of the home transport especially in terms of photochemical oxidation and global warming potential. The importance of the third aspect, product yield, was larger. Global warming emissions decreased by 25% when the product exchange was increased from 30% (as reported in literature) to 40% (as found in our own research). The fourth aspect was the impact assessment method, which was included due to the odd results initially found in the freshwater, terrestrial and human toxicity categories (Ziegler 2006). Ecoindicator 99 was compared with the CML method, and it was concluded that the impact categories that are comparable between the two methods did correspond fairly well, and that the main

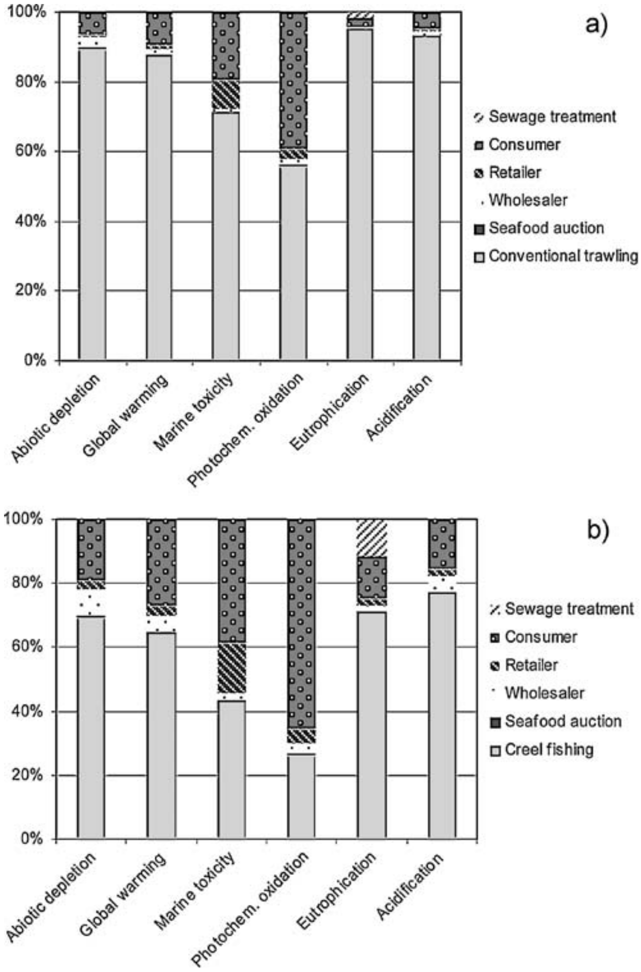

Fig. 4 Characterized LCA results for **a** conventional trawling, **b** creel fishing: *ABD* abiotic resource depletion (kg Sb eqs./FU), *GWP* global warming potential (10^2 kg CO_2eqs./FU), *MT* marine toxicity (10^4 kg 1,4-DB eqs./FU), *PCO* photochemical oxidation potential (kg C_2H_4 eqs./FU), *EP* eutrophication potential (kg PO_4 eqs./FU) and *AP* acidification potential (kg SO_2 eqs./FU)

results would not have changed had Ecoindicator 99 been used in the first place. To further analyze the reasons for the results in the toxicity categories, the Ecoinvent data concerning polyethylene, diesel, and passenger car transportation was replaced with data from the BUWAL database as the fifth and last aspect to be studied (again using the CML method for impact assessment which was the base case). In the case of diesel production, the choice of data had a small impact, while the use of BUWAL data led to a 23% increase in global warming emissions of passenger car transport, making it account for 11% rather than 9% of the overall global warming potential of the product life cycle. Choosing new polyethylene data completely altered the results for the toxicity categories, as discussed by Ziegler (2006), which is the reason why these categories were excluded from the present study.

4 Discussion

4.1 Discards

The discard level in conventional *Nephrops* trawl fisheries is a recognized problem. Actually, the northeast Atlantic trawl fishery for *Nephrops norvegicus* has the fifth highest discard ratio in the world (Catchpole et al. 2006). The weighted average discard for shrimp trawling (of which *Nephrops* trawling by definition is part) is 62%, the highest of all major types of fisheries in the world (Kelleher 2005). The amounts discarded in the studied fishery were even higher: more than four times the amount landed, while the number of individuals killed per individual landed were even higher, since the discarded specimens were smaller. With the exception of creel-caught *Nephrops* (which survives discarding, see below) discarding is a waste of a limited biological resource. Almost all of the individuals discarded will die and they could, if left in the sea, have been part of future catches. The most critical part of the discard comprises undersized Norway lobsters and groundfish species such as cod and haddock. Cod stocks are at historically low levels in this area and, since 2003, the International Council for the Exploration of the Sea (ICES) has repeatedly recommended a moratorium on cod fishing. Therefore, the introduction of the species-selective trawl, which decouples the *Nephrops* fishery from the groundfish fishery and makes the *Nephrops* fishery less dependant on the availability of fish quotas (Valentinsson and Ulmestrand 2008), is very positive. With regard to eutrophication potential, even though the landed catch represents an outtake of nutrients from the sea, this fishery causes an increase in the biological turnover of nutrients and contributes to eutrophication in the area due to the high amount of discard.

Discarding in the creel fishery has been studied much less. In 2005, a sampling was done on 18 fishing trips on creel fishing vessels to study the catch composition (Anon 2006, data presented in Fig. 2c). This data was used in the present study and indicated that the overall discard level was much lower in the creel fishery than in the two trawl fisheries. In addition, discard survival is higher, especially in the case of *Nephrops*, for which it has been estimated at 99% (Wileman et al. 1999). Trawling using a sorting grid led to a significant decrease in the discard of undersized fish compared to conventional trawling. Equally important is the catch composition of the selective trawl, for which 93% (by weight) of the landed catch is Norway lobster as opposed to 27% in the case of conventional trawls.

The species-selective trawl represents a great improvement with regard to one of the most crucial environmental aspects of *Nephrops* trawling. It is thus desirable to continue this positive development by making sure that

Table 1 The three most important processes in each impact category

Impact category	Fishing gear	Most important process	Second most important process	Third most important process
Global warming	Conv. trawl	Diesel combustion	Diesel production	Home transport
	Creel	Diesel combustion	Home transport	Diesel production
Eutrophication	Conv. trawl	Diesel combustion	Diesel production	Home transport
Eutrophication	Creel	Diesel combustion	Home transport	Diesel production
Acidification	Conv. trawl	Diesel combustion	Diesel production	Home transport
Acidification	Creel	Diesel combustion	Diesel production	Home transport
Marine toxicity	Conv. trawl	Diesel production	Diesel comb./antifouling emissions	Municipal waste incineration
Marine toxicity	Creel	Diesel production	Municipal waste incineration	Home transport
Photochemical oxidation	Conv. trawl	Diesel production	Home transport	Diesel combustion
Photochemical oxidation	Creel	Home transport	Diesel production	Diesel combustion
Abiotic resource depletion	Conv. trawl	Diesel production	Home transport	PP/LPG production[a]
Abiotic resource depletion	Creel	Diesel production	Home transport	PP/LPG production [a]

[a] at wholesaler

selective trawls are used more widely in the future. Another positive conclusion from the first evaluation of the grid introduction is that it seems to have caused no loss of commercial-sized *Nephrops*, rather the amount landed per unit of effort with selective trawls being the highest of all trawl categories targeting Norway lobster (Anon 2006). The overall environmental impact of the introduction of the selective grid in terms of other aspects such as fuel consumption and seafloor impact per unit landed remains to be evaluated.

4.2 Seafloor impact

The seafloor area swept and permanently affected by trawls per kilogram of trawled Norway lobster may seem large. It should be considered that *Nephrops* trawling is the dominant type of demersal trawling occurring in the area, but not the only one, and that Danish fishermen land more Norway lobster than do Swedes in this area. This implies that the total impact of demersal fishing is much greater than is presented here, where the intention was to relate the impact to a functional unit of Norway lobsters. However, it is impossible to analyze the Danish fishing effort in the same way, since their effort is not reported at the same geographical resolution. It should also be kept in mind that the recovery time indicated as high in MarLIN is 6 months to 5 years, so the use of 6 months (more than twice per year= permanently disturbed) leads to a very conservative estimate of the seafloor impact.

The impact of a creel landing on the seafloor when it is set is probably smaller per square meter than when the same area is swept by a trawl, but due to a lack of specific data concerning this matter and the great difference in area impacted by trawls and creels per kilogram landed, it was not further analyzed.

4.3 Safety and working conditions

Trawling is a more automated procedure than creel-fishing is. Setting and hauling creels is normally done manually by a person on deck, and working conditions are often far from optimal from both ergonomic and safety points of view (H. Aasjord, personal communication). Fishing is a high-risk profession, and fatal accidents are more common on smaller

Table 2 Impact Assessment results for a kilo of Norway lobster (or 300 grams of tails) from the sea to the table delivered by the two fishing methods. The chain on land is identical.

Impact category Unit	Abiotic depletion kg Sb eq	Global warming kg CO_2 eq	Marine toxicity kg 1,4-DB eq	Photochemical oxidation kg C_2H_4 eq	Eutrophication kg PO_4 eq	Acidification kg SO_2 eq
Trawling	0.18	27.8	3500	0.0033	0.077	0.18
Total when trawled	**0.20**	**31.7**	**4900**	**0.0058**	**0.081**	**0.19**
Creeling	0.047	7.18	1100	0.00092	0.0094	0.046
Total when creeled	**0.068**	**11.1**	**2500**	**0.0035**	**0.013**	**0.059**
Seafood auction	1.3E-4	0.00881	2.1	2.8E-06	6.1E-06	8.1E-05
Wholesaler	0.0059	0.540	49	0.00012	0.00025	0.0029
Retailer	0.0011	0.357	390	0.00017	0.00031	0.0014
Consumer	0.013	2.98	940	0.0023	0.0017	0.0090
Sewage treatment	9.6E-06	0.00183	0.97	2.9E-07	1.5E-03	6.8E-06

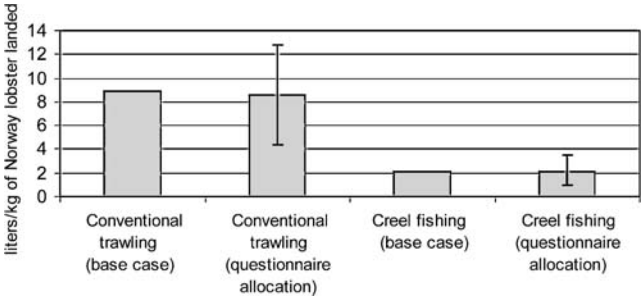

Fig. 5 Fuel consumption in the *Nephrops* fisheries, allocated according to catch composition as reported in the questionnaires (*error bars* represent standard deviation). Base case means allocation according to catch composition as reported in the EU logbook

vessels deploying passive fishing gear, on which fishermen often work alone, than on larger, more industrialized vessels (H. Aasjord, personal communication).

4.4 Ghost fishing

An additional risk is the loss of gear or gear material, a risk that is higher in creel fishing (Anon 2001) than in trawling and may partly explain the higher use of gear material in this fishery (Ziegler 2006). Lost creels and nylon netting can keep trapping animals, especially if there is still bait inside, subsequently killing them, a process termed ghost fishing (Anon 2001, 2003). Ghost fishing is a problem with some passive fishing gear types, especially gillnets. The use of degradable gear materials in creels and gillnets has been proposed as a means to mitigate this risk (Anon 2001).

4.5 Energy use

The fishing phase, with its high fuel consumption, dominated the life cycle in the case of both creel fishing and trawling for Norway lobster, as has been shown for many other types of seafood (Thrane 2004a, b; Thrane 2006; Ziegler et al. 2003). The difference is that the fishing phase of conventional trawling for Norway lobster, was even more important than later life cycle phases due to the extraordinary fuel consumption in this fishery, 9 l of diesel being consumed per kilogram of Norway lobster landed. Thrane (2004a) found a fuel consumption of approximately 6 l per kilogram of Norway lobster landed in Danish fisheries while Tyedmers (2001) found a much lower energy consumption: 37 MJ/kg corresponding to less than 1 l of diesel per kilogram. The low consumption found in the latter study was probably because Norway lobster was not the primary target species of the investigated fishery (which was cod) and that mass allocation was used to divide the fuel use between the cod and Norway lobster catch. Thrane, in contrast, used system expansion to avoid allocation between catch and by-catch, so none of these figures are really comparable. Had Thrane used economic allocation instead, the fuel consumption would have been approximately 4 l per kilogram of *Nephrops* (Thrane 2006), less than half that found in the present study. A considerable improvement option with regard to energy use lies in the more widespread use of creels which use much less fuel to land the same amount of Norway lobsters.

4.6 Baiting

The production of bait was responsible for 10% of the total energy consumption of creel fishing and 5% of the global warming emissions produced throughout the life cycle of the creel-fished lobsters. The amounts of bait used were higher than the amount of *Nephrops* caught. As small (undersized) lobsters can enter the creels to feed on the bait and then leave the creels again, this could be viewed as an input of nutrients to the marine ecosystem or as a type of semi-aquaculture, in which small lobsters are fed herring to grow to commercial size. Much of the bait that is left in the creels when they are hauled, however, is consumed by seabirds when discarded (it has to be replaced since it does not “smell” after a couple of days in the water). No studies have examined the proportion of bait actually consumed by the catch and the proportion leaving the creels with undersized specimens, but it can be assumed to be considerable. The use of artificial bait (flour-based dough containing fish oil) could be an improvement option to consider for the creel fishery.

4.7 Impact on Norway lobster stocks

The use of the Norway lobster stock on the Swedish west coast is currently considered to be sustainable, but it is recommended that fishing mortality should not increase due to uncertainty about the stock status in relation to threshold values (Ask and Westerberg 2007). The composition of the landed *Nephrops* catch is biased towards males, and both the creel and trawl landings comprise approximately 70% males and 30% females (Anon 2006). Of the females landed, more are found to be berried (carrying roe) in creel than in trawl catches. Berried females normally stay in their burrows, but they seem to be attracted by the bait and therefore enter the creels. This overrepresentation of berried females in the catches is discussed as one potential negative aspect of creel fisheries, since there is a risk of recruitment overfishing (i.e., that not enough eggs are produced) should the creel fisheries grow rapidly. Since the discard survival is very high for creel-fished *Nephrops* (Wileman et al. 1999), one way to mitigate this could be to protect berried females (as is done in the Swedish fishery for European lobster, *Homarus gammarus*).

4.8 Product quality

A study of the quality of Norway lobsters caught with creels and conventional trawls showed that there was a significant difference between the quality of Norway lobsters caught by creels and trawls (Evenbratt 2005). Creel-caught lobsters were in a better condition from the beginning and their quality decreased more slowly than their trawled relatives, they were also larger (all of which explains why they achieve higher prices). The quality assessment method used was quality index method, a sensory evaluation method. The scheme for Norway lobster is still under development and not fully validated, but was kindly made available by RIVO-DLO, the Netherlands (R. Schelvis personal communication). In a comparative LCA, one would ideally like the products to be identical with regard to function and quality. In this case, the quality of the products of the two fishing methods was shown *not* to be identical. The fishing method with the least resource use and emissions also had the highest catch quality, meaning that more of the catch will reach the end consumer and less of it end up as product waste, which increases the difference between the two even further. This underlines the previous conclusion in this study, that creel-fishing of lobsters is less resource-intensive than trawling.

4.9 Evaluation of the new gear regulations introduced in 2004

Comparing conventional and species-selective trawls with regard to discard clearly demonstrates that the new gear technology offers great improvement potential. The landings per unit of effort (LPUE) achieved with selective trawls were the highest of all the *Nephrops* trawl types analyzed in 2004 and 2005 (Valentinsson 2006). However, the amount of fish landed, representing a large part of landings in conventional *Nephrops* trawling, is much lower in species-selective trawling, just as intended. The impact of this on overall LCA results remains to be evaluated. Moreover, the distances steamed from port are shorter since grids are mainly used within 3–4 nautical miles of the coastline. All of these differences influence the resource use per kilogram of catch landed.

5 Conclusions and recommendations

The life cycle environmental impact of Norway lobster is dominated by the fishing phase being the main contributor to total impact, regardless of the particular fishing method. While this is a conclusion drawn from many of the performed seafood LCAs to date (e.g., Thrane 2004a, b; Ziegler et al. 2003), the contrast between fishing phase and post-landing phases in this case study was even more pronounced due to the extremely high fuel consumption for fishing per kilogram of Norway lobster landed. In addition, major differences between the environmental performance of creel and trawl fisheries for the species were demonstrated. Consequently, there are great potentials for improvement by replacing conventional trawls with creels. However, the safety and working conditions must be improved and the risk of recruitment overfishing must be mitigated by protecting berried females. A hypothetical future situation using currently available technology, in which 50% of Norway lobster landings are caught using trawls and 50% using creels (compared to 80% using trawls and 20% creels in 2005) would lead to 37% less seafloor impact, 36% less fish discard and 38% less discard of undersized *Nephrops*, as well as a 27% lower fuel consumption, while providing consumers with the same amount of Norway lobsters.

A more widespread use of species-selective trawls would reduce the discard problem of *Nephrops* trawling considerably, but its impact on the overall environmental impact of the fishery remains unknown.

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